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Life Cycle Assessment, ExternE and Comprehensive Analysis for an integrated evaluation of the environmental impact of anthropogenic activities

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ABSTRACT

The implementation of resource management strategies aimed at reducing the impacts of the anthropogenic activities system requires a comprehensive approach to evaluate on the whole the environmental burdens of productive processes and to identify the best recovery strategies from both an environmental and an economic point of view.

In this framework, an analytical methodology based on the integration of Life Cycle Assessment (LCA), ExternE and Comprehensive Analysis was developed to perform an in-depth investigation of energy systems. The LCA methodology, largely utilised by the international scientific community for the assessment of the environmental performances of technologies, combined with Comprehensive Analysis allows modelling the overall system of anthropogenic activities, as well as sub-systems, the economic consequences of the whole set of environmental damages. Moreover, internalising external costs into partial equilibrium models, as those utilised by Comprehensive Analysis, can be useful to identify the best paths for implementing technology innovation and strategies aimed to a more sustainable energy supply and use.

This paper presents an integrated application of these three methodologies to a local scale case study (the Val D'Agri area in Basilicata, Southern Italy), aimed to better characterise the environmental impacts of the energy system, with particular reference to extraction activities. The innovative methodological approach utilised takes advantage from the strength points of each methodology with an added value coming from their integration as emphasised by the main results obtained by the scenario analysis.

Contents

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1. Introduction

A key issue for sustainable development is to harmonise environmental protection with economic growth to assure future generation the fulfilment of goods and services demand and a better environmental quality through the improvement of eco-efficient productive processes. Moreover, the integration of environmental protection issues into management strategies is of fundamental importance to drive producers and consumers towards the choice of technologies and products with a reduced environmental impact.

The Sixth Environment Action Programme [1] sets out the priorities for the European Community up to 2010, underlining the necessity of a strategic approach based on the optimisation of resources management to face the increasing environmental problems. In fact, a bare normative approach is not sufficient to limit the environmental damages due to anthropogenic activities as significant changes in production and consumption patterns are required to achieve an effective improvement of air quality as well as climate change mitigation. In this context, it is of fundamental importance to characterise in detail the environmental burdens associated to the different phases of the life cycle of products, the energy-environmental performances of technologies and to exploit the correlations among the supply and end-use sectors.

A Comprehensive Analysis of the anthropogenic system is thus necessary to estimate the overall environmental impact and to take into account feedbacks among the different sectors involved. However, to perform an in depth investigation of the local systems and to better understand the total impact of anthropogenic activities, Comprehensive Analysis should be integrated with other tools as Life Cycle Assessment (LCA) and external cost evaluation.

These tools are in fact of fundamental importance for taking into account the contribution of the different life-cycle phases and the economic value of the environmental damage, in order to define policy and tariff strategies capable of reducing the overall impact of productive activities and promoting technology innovation.

The interest on these issues have been growing in recent years, and many studies [2,3] are being devoted to the development of decisional tools based on analytical models capable to identify sound and economically feasible energy-environmental strategies.

This work shows an example of soft-linking integration between the Comprehensive Analysis (MARKAL models generator), Life Cycle Assessment (LCA) techniques and externalities evaluation to explore the environmental impact of products and processes in terms of primary pollutants concentration as well as their main effects on environment (e.g. acidification, greenhouse potential, . . .) and include in resources' price the economic value of potential environmental damages.

2. Methodology

Life Cycle Assessment, evaluation of external costs and Comprehensive Analysis are the fundamental methodologies used for the evaluation and the minimisation of the environmental impact of the commodities production system (in terms of physical–chemical parameters and damage costs). However, they are based on different scientific assumptions that lead to different results that could be usefully complemented.

The main features of each methodology are briefly summarised in the following.

2.1. The Life Cycle Assessment

The LCA "is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environmental improvements" [4].

In particular, LCA is aimed to the identification and quantification of physical flows of energy and materials, focusing on single technologies or processes and it is very useful to compare the environmental performances of products with the same functionality or to find out the bottlenecks of productive processes. LCA is time specific and, in general does not allow analysing the effects of technology substitution on medium–long term as well as the cost-effectiveness of different choices.

Some attempts to have a monetary evaluation of products and processes has led to integration of conventional LCA with Life Cycle Cost Analysis (LCC) [5] and input–output economic analysis (IOA-LCA) [6,7].

In particular, LCC follows the typical approach of LCA evaluating analytically all costs experienced during the life cycle of equipments (from inception to disposal) in order to choose the cost-effective approach from a series of alternatives. On the contrary, IOA-LCA is a method based on the monetary flows induced throughout the economy from a given sector output. It provides an automatic evaluation of energy consumption and pollutant releases linked to monetary transactions between the involved productive sectors, which are based on average values of emissions and energy consumption per economic unit of output. This feature makes IOA-LCA very useful for sector studies but not much reliable for detailed analysis. In this study, the modelling tool used for LCA analysis is the GEMIS software (Global Emission Model for Integrated Systems database) developed by Oko-Institut [8].

2.2. The Comprehensive Analysis

Comprehensive Analysis [9] focuses on a global system level, with a bottom-up characterisation of its components. The analysed energy–environment system is represented as a network (the "so-called" Reference Energy and Material System—REMS) which describes energy and material flows, from extraction to end-use demands/waste production, through conversion processes. Each element in the network is characterised by a set of technologies described by means of technical–economic data (e.g., capacity, efficiency, average lifetime, availability, investment costs, operating and maintenance costs, date of commercialization, etc.) and environmental parameters (e.g. pollutants emitted). A linear partial equilibrium model is set up to represent the relationships among the system's components and the boundary conditions over a planning time horizon (usually from 20 to 50 years) chosen by the

users, divided into time periods of fixed or variable length. The optimal solution found by the model determines the energy system configuration which minimises the cost of energy services in compliance with the considered exogenous constraints (i.e. availability of resources and technologies, emission targets, etc.).

Among the partial equilibrium models generators, MARKAL [10,11] is one of the most widespread tools, being used in many OECD countries to perform energy-environmental analysis on supra-national, national and regional level. A first version of MARKAL was developed in the end-seventies at the Brookhaven National Laboratory of New York in a collaborative effort under the auspices of the International Energy Agency-Energy Technology Systems Analysis Programme (ETSAP) [12] and the United States Department of Energy and was mainly addressed to optimise energy production in response to oil crisis. At present, its flexibility allows modelling systems with very different features and to examine a variety of policy issues related to environmental protection, sustainable use of resources and security of supply.

MARKAL is a linear programming optimising models generator whose main inputs are represented by the demand for energy services by sector (e.g. dwellings heating, lighting, water heating, air conditioning, etc.) together with resource availability and environmental constraints. The optimal solution selects the best set of technologies and fuels that, for each time period and over the entire time horizon, allows to satisfy the end-use sectors' energy demand and to achieve the prefixed environmental targets at the minimum feasible total system cost [13–16].

The model structure allows the users to include damage functions and coefficients to get an estimate on medium–long term of the environmental costs due to atmospheric pollution as well as to internalise such external costs in goods and services prices [17].

From the model's results, it is therefore possible to identify the cost-effective strategies under superimposed constraints, to evaluate the effects of different implementation mechanisms (regulations, taxes and subsidies, emissions trading) and the role of technology innovation. In particular, different competing technologies are compared in terms of techno-economic and environmental performances. In this framework, costs analysis (in particular focused on shadow prices of resources and reduced costs of technologies) is used to find out the best available solutions and to define the investment strategies that foster their market penetration.

2.3. The ExternE approach

The methodology developed in the framework of the ExternE (Externalities of Energy) project [18] is the main international reference for the monetary evaluations of environmental burdens as well as the internalisation of external costs related to the energy sector. ExternE [19–26] is a research project of the European Commission launched in collaboration with the US Department of Energy in 1991 that established a methodology and accounting framework for the comparable assessment of the externalities from a wide range of different fuel cycles. The main objective of this project was to apply this methodology to a wide range of different fossil, nuclear and renewable fuel cycles for power generation and energy conservation options, and subsequently it has been extended to address the evaluation of externalities associated with the use of energy in the transport and domestic sectors and to also include a number of non-environmental externalities such as those associated with security of supply.

This methodology is constantly updated to improve the evaluation of impacts and an estimation of associated costs [27,28].

2.4. A combined approach for energy systems analysis

A crucial point of Comprehensive Analysis is the level of detail of energy and materials flows representation which is related to a sector by sector characterisation of technologies. A combination of global analysis with subsystem analysis is usually envisaged to obtain more specific responses and to perform a strategic energy-environmental planning on medium–long term.

In this framework, integrating Comprehensive Analysis with LCA and external costs evaluation into a unique modelling approach allows to take advantage from the inputs of the three methodologies, increasing the level of detail relatively to the characterisation of the overall life cycle impact, associating an economic value to each atmospheric pollutant and evaluating their effects in a long term perspective.

In such a context, LCA feeds into the energy models detailed "cradle to grave" information on resources and technologies; ExternE provides an estimate of cost externalities per emission/burden whereas Comprehensive Analysis, taking into account these data, allows defining the minimum feasible system cost and the optimal energy and technology mix [29]. It is therefore possible to perform a so called "LCA of energy systems" [30] that points out the cause–effects relationships among sectors, taking into account at the same time the atmospheric pollutants and their effects on the environment.

In this way, both the external and internal environmental impacts of energy systems can be analysed contemporaneously (Fig. 1).

From an operative point of view, the results of LCA are introduced in the comprehensive model by adding new indicators in the model's set of environmental variables (SET ENV), which usually includes only the typical primary pollutants (NO_x, CO, CO_2, SO_2, TSP, etc.).

Besides that, the considered environmental pollutants' effects (Acidification, Global warming, Smog) are modelled by utilising the "Multiple Emissions Accounting (MEA)" variable that is a

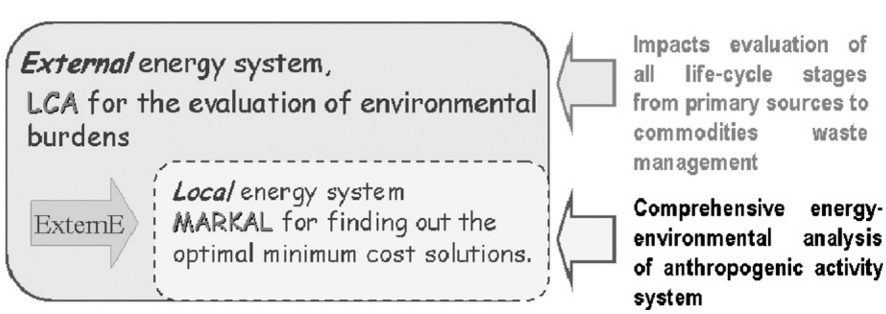

Fig. 1. Integrated approach for energy systems analysis.

weighted linear combination of primary pollutants (1):

$$\mathrm{env(MEA)} = K_1 \cdot \mathrm{env}_1 + \cdots + K_n \cdot \mathrm{env}_n \tag{1}$$

where the weight factors K_n define the unitary contribution of each pollutant env_n to the represented indicator (the values utilised were taken from the IPCC—Intergovernmental Panel on Climate Change documentation and other governmental regulations [31]).

In addition to that, the damage costs of pollutants (the ExternE values) are inserted in the MARKAL model by a "damage function" attribute that represents the estimated external cost per unit of pollutant emitted.

The damage per pollutant (DAM(env)) is therefore modelled as (2):

$$\mathrm{DAM(env)} = \mathrm{EV_{coef}(env)} \cdot \mathrm{EM(env)} \tag{2}$$

where EM(env) is the total emission of the "env" pollutant, $\mathrm{EV_{coef}}$(env) is the value of external cost for unit of "env".

Subsequently, the computation of environmental damages can be performed with two different approaches: "*ex post*", without feedback into the optimisation process, or "*ex ante*", adding the damage function to the objective function, to take its value into account in the optimisation process [32].

3. The reference energy and material system of Val d'Agri

The integrated methodological approach was applied to the characterisation of Val d'Agri energy system, that concerns a small area of Basilicata Region (Southern Italy) in which is located the largest Italy oilfield with an average production of 90,000 oil barrels per day that is going to reach more than 100,000 barrels per day within next years [33,34].

The Val d'Agri area is also a place of great interest from a naturalistic and architectural point of view and was recently acknowledged as a national Natural Park. The coexistence of a natural park and oil fields drives the attention towards the environmental problems caused by energy uses and, in particular, from the increasing mining activities that may cause irreparable damages, compromising the environmental sustainability of the whole area.

The REMS of the Val d'Agri energy system schematises the energy and materials flows through the intermediate conversion and end-uses processes. Each component of this network was characterised from a technical, economic and environmental point of view, further technical details can be found in a previous paper [35].

As concerns the *supply side*, the oil extraction activities have, as said before, an important role for their high impact on the environment. In 2000 electricity produced from renewable was about 89% (133 GWh/year, of which 116.6 GWh/year by hydroelectric power plants, 16.58 GWh/year by wind and 0.06 GWh/year by small photovoltaic plants). The remaining 11% was produced by thermoelectric power plants, mainly gas fuelled.

According to the Regional Energy Plan estimations (PER) [36] the renewable share could increase up to 93% with the installation of mini-hydroelectric (16.4 GWh/year), PV (20.78 GWh/year) wind (181.797 GWh/year) and biomass (40.5 GWh/year) power plants. These capacity potentials were taken into account to model in a realistic way the system development over the considered time horizon.

The end-use demand is about 2,486,912 GJ of which 5% fulfilled by endogenous resources. A detailed sectoral breakdown of energy end-use was estimated for year 2000 with reference to the available statistical data sources [37–39], revealing that Residential and Industry are the prevailing consumers, each of them accounting for 34% (Table 1).

The LCA information were essential to model in depth the impacts of both oil extraction activities and electric power generation (EPG) technologies (Fig. 2), taking into account the construction and disposal phases and completing the data already available on the operating phase.

Table 1
Final energy consumption by sector—year 2000 (GJ)

	Wood	Coal	Other solids	Natural gas	LPG	Diesel	Fuel oil	Electricity	Total
Residential	148,989	2,001		175,920	53,546	5,973	–	185,029	2,001
Space heating	148,989	1,747		140,384	33,413	5,585	–	2,352	1,747
Water heating		196		23,221	3,962	388	–	42,109	196
Cooking		58		12,314	16,171	–	–	7,857	58
Refrigeration		–		–	–	–	–	45,748	–
Washing machine		–		–	–	–	–	24,885	–
Dishwasher		–		–	–	–	–	7,190	–
Lighting		–		–	–	–	–	29,589	–
other electric uses		–		–	–	–	–	25,299	–
Commercial and services		189		69,881	9,598	956	–	83,091	189
Public administration		–		–	–	–	–	10,340	–
Public illumination		–		–	–	–	–	25,867	–
Agriculture		–		–	12,765	792,520	–	–	–
Industry		55,864	8,658	171,359	2,991	13,442	37,100	312,658	602,100
Food and drink		877	230	27,529	484	743	5,891	24,624	–
Other industries		552	–	184	295	517	3,750	5,895	–
Paper		22	–	2,577	32	55	1,421	2,541	–
Chemical		38	17	12,426	235	131	3,647	30,683	55,864
Rubber and plastic		94	42	15,922	124	326	2,567	18,082	877
Buildings		–	1,880	304	111	3,442	1,880	2,641	552
Mining		87	–	13,997	68	632	607	2,772	22
Mechanic		277	–	10,264	332	475	1,089	8,869	38
Iron and steel industry		39,969	–	36,810	438	170	887	59,575	94
Textile		180	–	4,923	179	392	3,177	58,663	–
Electric energy, gas and water								42,051	87
Building materials		13,605	6,517	42,445	379	6,517	10,520	47,151	277
Glass-ceramics		164	–	3,978	314	44	1,665	9,111	39,969
Total	148,989	58,054	8,685	428,884	86,177	1,060,833	40,031	655,259	2,486,912

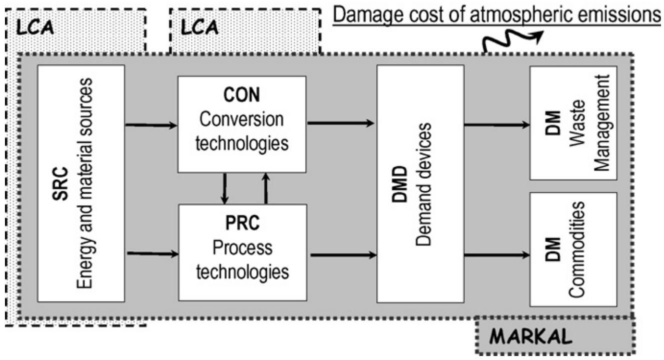

Fig. 2. Application of LCA to sector analysis.

Table 2
Weight factors used for calculating aggregated indicators in MARKAL-VdA [31]

Environmental burdens	Pollutants	Weight factor
Acidification (ton SO_2eq)	SO_2	1
	NH_3	1.88
Smog (ton SPMeq)	Particulate	1
	PM10	1
Greenhouse (ton CO_2eq)	CO_2	1
	CH_4	11

Table 3
Environmental impacts of oil extraction activities—year 2000

Impact category	Unitary impact per kton of oil produced	Total impact
Acidification (kg SO_2eq)	1,770	800,040
Greenhouse (kg CO_2eq)	283,000	127,916,000
Smog (kg SPMeq)	677	306,004

3.1. Oil extraction activities

Oil mining activities represent the main cause of environmental damage in the local area, therefore, their impacts were analysed with reference to the different phases: construction of perforations infrastructures, drilling activities, flaring, (i.e. the emissions caused by the combustion in torch of the gas associated to oil) and the so-called "blow-out" (uncontrolled eruptions that can take place for the income of fluid of layer in the sink).

Three main categories of environmental burdens were computed using LCA: Acidification, Smog and Greenhouse effect. They were introduced into the Val d'Agri model by the "Multiple Emissions Accounting" variable (see Section 2.4), using the weight factors reported in Table 2.

In Table 3 the total impacts of oil extraction activities to each impact category are reported, with reference to the average oil production in 2000, emphasising the huge contribution to all the considered impact categories.

These results underline the importance of devising "*ad hoc*" solutions for this sector, addressed both to protecting the environment and to increasing the security of energy supply.

3.2. Electric power generation technologies

Construction and dismantling phases of electric power generation (EPG) technologies may strongly contribute to environmental degradation. Thus LCA was applied to the characterisation of the environmental impact of the already existing plants and the ones whose installation is foreseen by the PER within the planning time horizon.

Table 4 reports for the considered EPG technologies the unitary impact coefficients and the total impacts estimated for Greenhouse effect, Acidification and Smog [8] considering the extrapolations of the PER [36]. It can be seen that greenhouse effect has a high value in all the plants, with the most significant contribution belonging to hydro and PV. Biomass technologies contribute remarkably to all the considered impact categories.

4. Scenario assumptions

The multi-period structure of MARKAL models generator requires the specification of the basic energy system features on the planning time horizon in terms of end-use energy demands, technology and fuels availability. Moreover it is necessary to define quantitatively the variations of the scenario parameters (e.g. emission levels, aggregated environmental impacts, external costs of pollutants) and their variations to perform the scenario analysis.

For the Val d'Agri energy system, a 27-year time horizon (1996–2023), divided into nine time periods of equal length, was considered. The base year is 1997 but the reference year for energy consumption is year 2000. A constant demand of goods and services on the analysed time horizon, was considered taking into account a negative trend of population growth rate (−7% between 1991 and 2001) [40], and the effects of the new building standards and technology turnover in end-use sectors. A 4% discount rate was adopted for costs actualisation.

The *Reference scenario* (*Business As Usual—BAU* case) implements the PER hypotheses [36] as concerns the contribution of renewable sources (PV, wind, biomass and mini-hydroelectric). In fact, the BAU case models the evolution of the reference energy system without exogenous environmental constraints providing the baseline for scenario analysis. Efficiency increase due to technology turnover as well as energy conservation measures in residential (double glazed windows and thermal insulation of roofs, ceilings and external walls) were taken into account.

Two additional scenarios were defined to examine and compare the effects on the energy system's configuration, costs of constraints on environmental impacts and eco-taxes on the main

Table 4
Unitary indicators and total impacts estimated for EPG technologies

	Greenhouse effect		Acidification		Smog	
	kg CO_2eq/GJ	kg CO_2eq	kg SO_2eq/GJ	kg SO_2eq	kg SPM/GJ	kg SPM
Mini-hydro	0.867	51	0.002	0.11	0.001	311.60
Wind	6.00	358	0.01	0.86	0.005	61.95
Hydroelectric	8.01	3363	0.01	6.22	0.006	467.71
Thermoelectric	64.21	352	0.12	6.87	0.01	1865
PV	44.34	3363	0.12	8.99	0.11	6.48
Biomass	9.35	1362	0.91	133.10	4.44	1322

Table 5
Main scenarios assumptions

Scenario	Cases	Main features	Constraints	External costs
Reference	BAU	Do nothing	No	All pollutants, *ex post*
Impacts	Greenhouse	Constraint on Greenhouse Effect	−1.1% Greenhouse Effect	All pollutants, *ex post*
	Acidification	Constraint on Acidification	−0.6% Acidification	All pollutants, *ex post*
	Smog	Constraint on dusts level	−1.5% Smog	All pollutants, *ex post*
	Mix	Combined constraint on environmental impacts: Greenhouse Effect + Acidification + Smog	−1.1% Greenhouse Effect, −0.56% Acidification, −0.02% Smog	All pollutants, *ex post*
Eco-taxes	TAX-CO2	19 Euro/ton on CO_2	No	CO_2, *ex ante*
	TAX-NOX	7100 Euro/ton on NO_x	No	NO_x, *ex ante*
	TAX-SO2	5000 Euro/ton on SO_2	No	SO_2, *ex ante*
	TAX-TSP	12000 Euro/ton on TSP	No	TSP, *ex ante*
	TAX-VOC	2800 Euro/ton on VOC	No	VOC, *ex ante*
	TAX-TOT	Taxes on all the analysed emissions (CO_2, NO_x, SO_2, TSP, VOC)	No	All pollutants, *ex ante*

pollutants. As shown in Table 5, the *Impacts scenario*, includes four cases that analyse the effects of exogenous constraints on aggregated impacts indicators (Greenhouse effect, Acidification, Smog, and a combination of all the indicators), whereas the *Ecotaxes scenario*, includes six cases in which the external costs were introduced as taxes on local air pollutants (NO_x, SO_2, TSP and VOC) as well as on CO_2, to evaluate their influence on the system configuration and to assess their synergies.

In particular, the SO_2, NO_x, VOC and TSP external costs are the values reported for Italy in the Benefits Table database (BeTa) [41], developed by *netcen* (AEA Technology) for 15 countries of the European Union. As concerns carbon dioxide, as well known, the determination of the external cost is affected by a large uncertainty, due to the large set of harmful effects on human health and on the environment and to the long time horizon (100–500 years) on which these impacts could span [20]. Therefore the values are ranging in a wide interval (from 0.1 to 139 euro/ton [42,43]). As concerns our case study, an average value of 19 Euro/ton CO_2 [44] was considered.

4.1. Post-optimal analysis

The main results obtained by the optimization routine are described in terms of fuel mixing, technological configuration, environmental impacts and the variations of total system cost.

4.1.1. BAU scenario

The Reference scenario results described in detail in [35] are briefly resumed here.

The optimization of energy uses performed under the BAU assumptions conveys in a 10% reduction of energy consumption on the whole time horizon (15% of which due to energy savings obtained by insulation interventions in buildings and the remaining 85% due to more efficient end-uses technologies).

As concerns the fuel mix, fossil fuels are substituted by a massive use of natural gas driven by a large availability of combined natural gas boilers in Residential, which replace mainly LPG and diesel boilers.

In electricity production there is an increased use of endogenous renewable sources that fosters a reduction of electricity import (Fig. 3). On average, in 2009 the 85% of the electricity will be produced from renewable (70% hydro, 9% wind and 6% waste incineration) according to the deployment of renewables energy sources foreseen by the PER [36], with the exception of biomass and PV for which specific support policies are necessary in order to reduce the gap due to their high investment costs.

4.1.2. The "Impacts" scenario

The Impacts scenario is aimed to exploring the possibility of reducing three of the most important effects due to atmospheric pollution: Greenhouse effect, Acidification and Smog. These indicators were chosen as the most effective to focus on the most

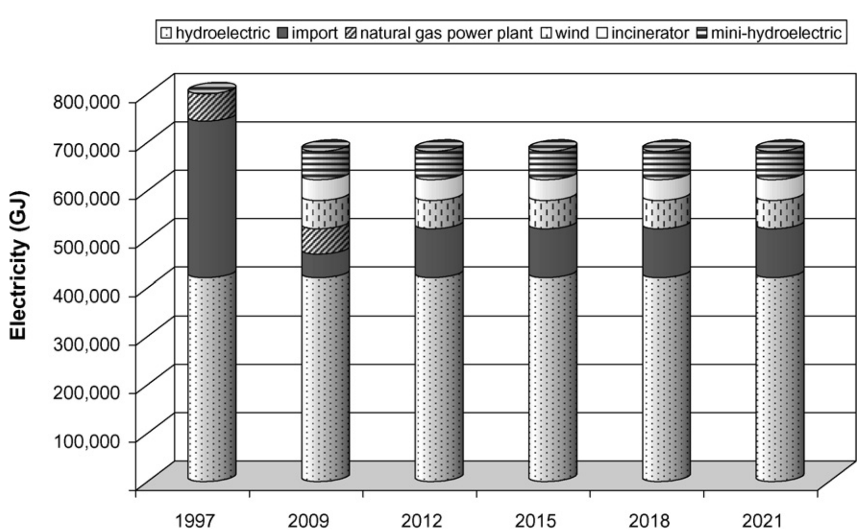

Fig. 3. Contribution of different sources to the electricity production—BAU scenario.

dangerous effects caused by local air pollutants (SO_2, NO_x and particulate matter—PM10 and PM2.5) as well as to examine the synergies between local and global pollutants. In fact, as well known, CO_2 has a major role in the greenhouse effect, SO_2 and NO_x emissions are primary contributors of acid rains, whereas particulate matter (which is formed in the atmosphere by condensation or the transformation of emitted gases such as SO_2 and VOCs) is a main contributor to smog and causes many adverse effects on human health and materials damage.

The total consumptions obtained in the four cases are pretty similar to the ones obtained in the Reference scenario; however in the Greenhouse case a further 0.6% reduction of energy consumption is achieved.

As concerns electricity production, a larger use of renewable fuels as well as of the technologies with a lower overall environmental impact can be noticed.

In particular, some differences in technology choice characterise the four cases, even if conventional power plants are still used on the overall time horizon and the most expensive new technologies, that require high investment costs, as PV are not chosen by the model.

In the Acidification case, mini-hydroelectric is the preferred technology (which is used at the maximum allowable capacity also in the Smog case).

In the Greenhouse and Mix cases the biomass plant substitutes conventional thermal power plants and, among renewable technologies wind power is the less used (−6% and −18% respectively).

In the Smog case, as already said mini-hydroelectric is the preferred technology whereas the biomass plant is not activated and wind power is the less used renewable technology, because of its high contribution to this effect.

As concerns the synergies among local and global effects, the constraints on Acidification and Smog induce a reduction of greenhouse effect of about 1%, CO_2 emissions decreasing respectively 1.5%, 3%, 5.7% and 7.3% in the Smog, Acidification, Mix and Greenhouse cases.

Table 6 summarises the total emissions of TSP, VOC, NO_x, SO_2 and CO_2 on the overall time horizon for the analysed scenarios (the minimum values are highlighted in bold). It can be seen that the lowest values for NO_x and SO_2 are obtained in the Mix case (respectively −0.05% and −1.19% respect to the BAU case), for TSP and VOC in Acidification and Smog (respectively −0.12% and −0.01%). As concerns CO_2, the minimum is achieved obviously in the Greenhouse case (−7.27% respect to the BAU case) but a noticeable reduction is observed also in the Mix case (−5.70% respect to the BAU case).

These data highlight the effectiveness of the constraints on the aggregated impacts that allow reducing single pollutants emissions emphasising at the same time the cause–effects relationships.

The introduction of exogenous environmental constraints causes an obvious increase of the total system cost (Fig. 4), the highest value being achieved in the Greenhouse case (1207 MEuro) and the smallest in the Smog case (1039 MEuro).

Table 6
Total emissions of the Impact scenario

Scenarios	Cases	TSP (ton)	VOC (ton)	NO_x (ton)	SO_2 (ton)	CO_2 (ton)
Reference	BAU	3345	38,371	155,589	15,256	2,627,645
Impacts	Greenhouse	4247	39,222	157,735	15,093	**2,436,617**
	Acidification	**3341**	**38,367**	155,565	15,078	2,551,446
	Smog	3342	**38,367**	155,594	15,080	2,588,525
	Mix	3740	38,740	**155,514**	**15,075**	2,477,833

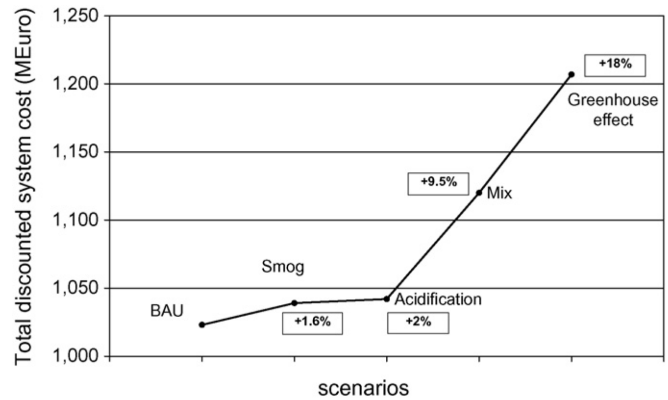

Fig. 4. Total system costs of Impact scenario's cases.

4.1.3. Evaluation of external costs

The introduction of external costs allows evaluating the effects of environmental pollution in terms of social costs. The economic value of damage is determined by multiplying the external cost by pollutant for the amount of emissions released in the considered scenarios. Two kinds of evaluation can be considered: *ex post*, in which the environmental damage is computed without feedback into the optimisation process and *ex ante*, in which the internalization of external costs is done by introducing eco-taxes to consider the external costs in the optimization of the energy system costs. In the first case only the economic value of damage is estimated whereas in the latter it is possible to investigate on the economic impact of pollutant emissions and the role of external costs in devising the optimal strategies for resources management [42].

4.1.3.1. The ex post approach. In the *ex post* evaluation the overall external costs are simply added to the cost function with no effect on the determination of the optimal solution. This allows to estimate in monetary terms the environmental impacts of atmospheric emissions in different scenario hypotheses.

The values of damage function obtained by the *ex post* optimization of the analysed cases are reported in Fig. 5. In general a 0.1% variation is observed among them. The Greenhouse case is the most expensive as a constraint on greenhouse effect has no effect on the other pollutants acting only on CO_2 emissions, whose value is very low (19 Euro/ton). The Acidification and Smog cases show a slight reduction of the external costs according to the observed decrease of SO_2 and NO_x emissions.

4.1.3.2. The ex ante approach. The introduction of environmental taxes emphasises the role of environmental damage in the definition of resources prices and in the comparison of technologies performances in terms of both direct and indirect effects. In fact, eco-taxes could determine a reduction of emission levels depending on their effect on energy system configuration.

The eco-taxes scenario examines, in an *ex ante approach*, the effect of eco-taxes on the main local air pollutants plus CO_2. Five cases are considered, as shown in Table 5.

From the results reported in Table 7 it can be seen that as concerns NO_x (TAX-NOX case) a 0.71% reduction of emissions could be obtained, whereas for SO_2 (TAX-SO2 case) the reduction percentage is 0.31%.

A negligible reduction of emission levels is observed for the other cases. In particular, for CO_2, there is not any feedback on the emissions considering an external cost of 19 Euro/ton whereas a small reduction of emissions (−0.5%) is achieved considering its highest value (139 Euro/ton [42]).

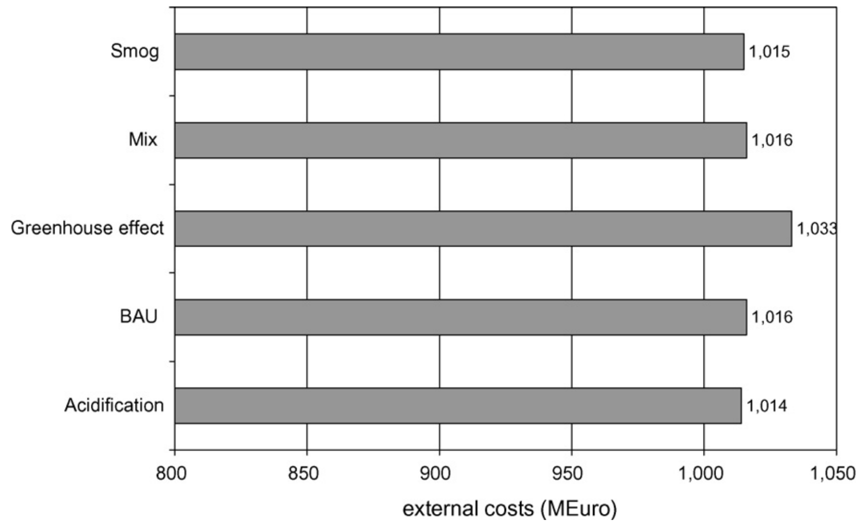

Fig. 5. Total external costs (*ex post* evaluation).

Table 7
Total pollutant emissions on the full time horizon—eco-tax scenario

Scenarios	Cases	TSP (ton)	VOC (ton)	NO_x (ton)	SO_2 (ton)	CO_2 (ton)
Reference	BAU	3345	38,371	155,589	15,256	2,627,645
Eco-taxes	TAX-CO2	3345	38,371	155,589	15,256	2,627,645
	TAX-NOX	**3339**	38,361	154,488	15,260	2,628,419
	TAX-SO2	3346	38,371	155,625	**15,208**	2,648,299
	TAX-TSP	3345	38,371	155,585	15,255	2,627,645
	TAX-VOC	3345	38,371	155,585	15,255	2,627,645
	TAX-TOT	**3339**	**38,360**	**154,480**	15,236	**2,626,567**

Besides a straightforward effect on the related pollutants, the eco-taxes induce a reduction of the emission levels of correlated untaxed pollutants that in some cases is higher that the one achieved in the correspondent case (Table 7). As an example, the eco-tax on NO_x induces a 0.18% decrease of TSP emissions whereas the one obtained in the TAX-TSP case is 0.03%. The same happens for VOC emissions that seem to be not influenced by a direct eco-tax, but show a slight decrease (0.03%) under a tax on NO_x. A similar behavior can be observed also for CO_2, whose emissions decrease 0.79% in the case TAX-SO2.

To highlight the synergies among pollutants, the additional case TAX-TOT was thus defined including in the model the eco-taxes of the whole set of pollutants (CO_2, NO_x, SO_2, TSP and VOC). The optimization of such a case induces a decrease of the emissions of all the pollutants considered. In particular, for NO_x, TSP and VOC the maximum allowable percentages are achieved (respectively: −0.71%; −0.18% and −0.03%) whereas SO_2 and NO_x decrease respectively 0.13 and 0.04%. Comparing these results with the ones obtained for the Impacts scenario it could be seen that a tax on NO_x emissions is effective not only for NO_x but also for TSP and VOC that achieve in this case the lowest values. On the contrary, for SO_2 and CO_2 a constraint on the related impact categories is more effective.

The total discounted system's costs obtained in the *ex post* and *ex ante* approach, including the external costs on all the pollutants are respectively 2039 MEuro (BAU case) and 1959 MEuro (TAX-TOT case), highlighting that a 4% of cost reduction could be achieved including the environmental taxes in the objective function.

5. Conclusions

The integration of partial equilibrium models with LCA and ExternE allows to estimate in depth the overall environmental impact due to anthropogenic activities and to devise sustainable strategies for energy systems development that include the social costs due to atmospheric pollution. In this framework the MARKAL models generator structure is particularly suitable to integrate the parameters coming from the different methodologies into a unique modeling platform achieving their operative integration and a long-term evaluation of the effects of environmental damage also from an economic point of view.

In this paper a soft linking between LCA, ExternE and Comprehensive Analysis is presented, with reference to a local case study (Val d'Agri energy system) being focused to better characterise the impact of oil mining activities and the role of REMS in energy supply. The scenario analysis shows once more that efficiency increase and energy saving are privileged tools for driving a steady reduction of energy consumption, whereas renewable energy sources have a key role in the supply system but need an in depth characterisation of the construction and dismantling phases, that may contribute heavily to environmental damage.

In this sense, the integration with LCA is particularly important for the full evaluation of environmental impact of endogenous anthropogenic activities, emphasising the role of the supply system as well as the limits of RES technologies implementation.

As concerns the integration of externalities, eco-taxes are important to estimate fair prices of resources and to promote the use of eco-compatible technologies and resources. In fact, including the environmental component in the costs of goods and services, it is possible to reduce the cost gap among traditional and innovative technologies.

As concerns local scale investigations, an in depth knowledge of the territorial peculiarity is a prerequisite to reduce uncertainty and to get sound results effectively implementable.

To conclude, this work set the basis for defining a general applicable methodology that could drive to the definition of advanced support tools for decision makers that can assure the coherence of strategies at different time and spatial scales, demonstrating a fundamental importance for the assessment and the implementation of energy-environmental policies.

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